HYDRAULIC/PNEUMATIC TOMOGRAPHY:

A New Site Characterization Method

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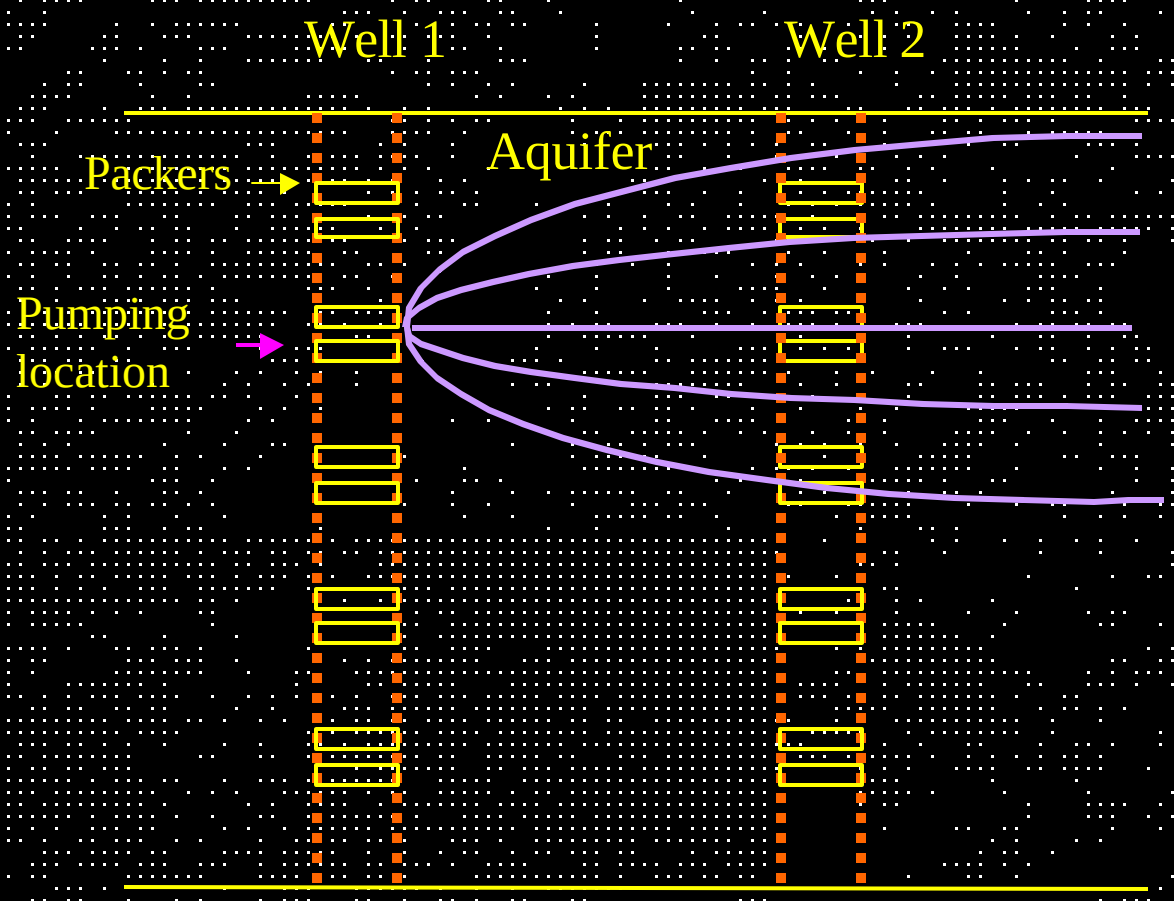
What is hydraulic tomography?



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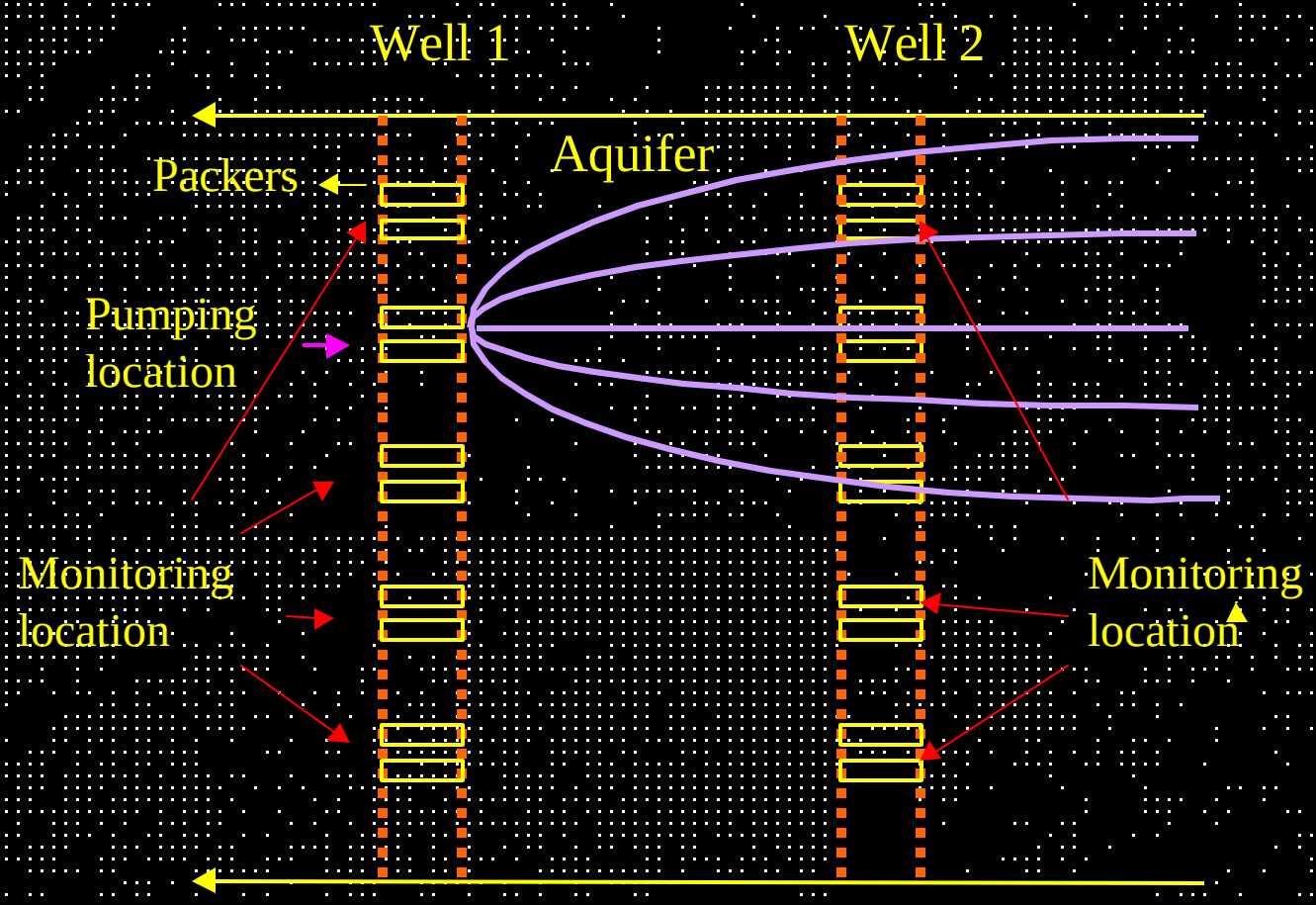

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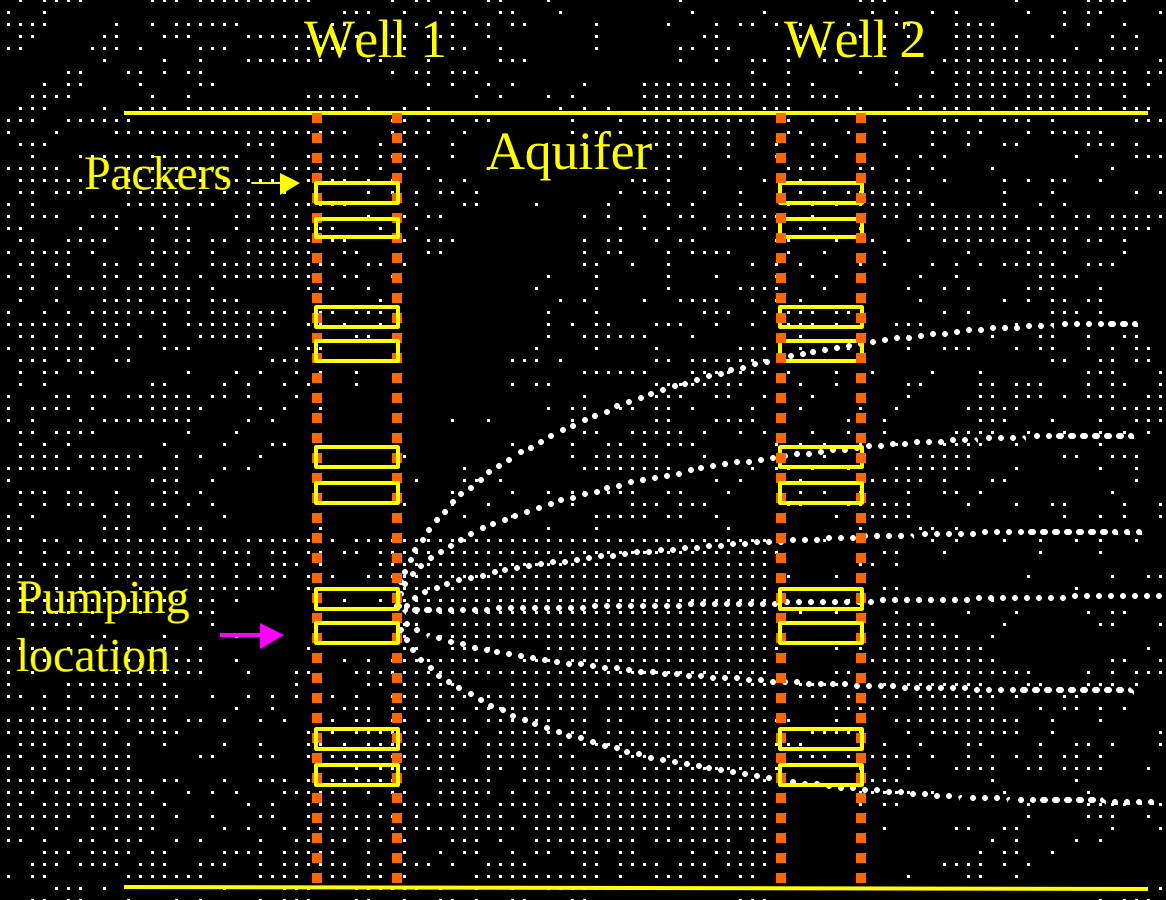

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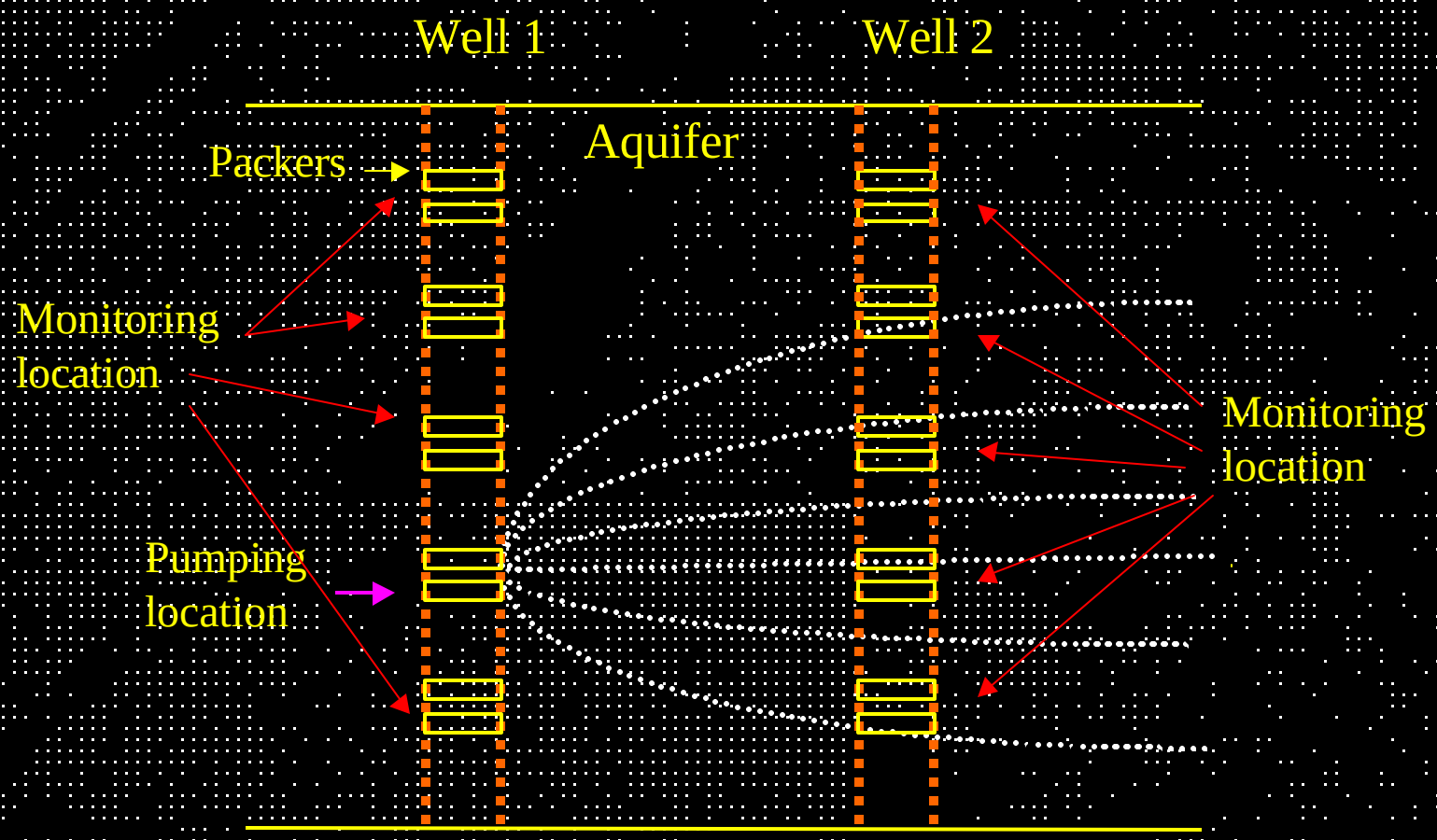


A large number of pumping/pressure data sets

↓

Inverse Model

↓

Detailed 3-D hydraulic conductivity distribution

Hydraulic Tomography = Sequential Pumping Test

Why hydraulic tomography?

- Prediction at high resolutions requires detailed knowledge of heterogeneity.
- Classical aquifer tests give the averaged conductivity over a large volume of aquifer.
- Core samples and small scale in-situ borehole tests require a large number of drillings: costs .
- Geophysical survey? Difficulties to relate its results to hydrological parameter values.

Any robust inverse model for hydraulic tomography?

1. Classical inverse methodologies:

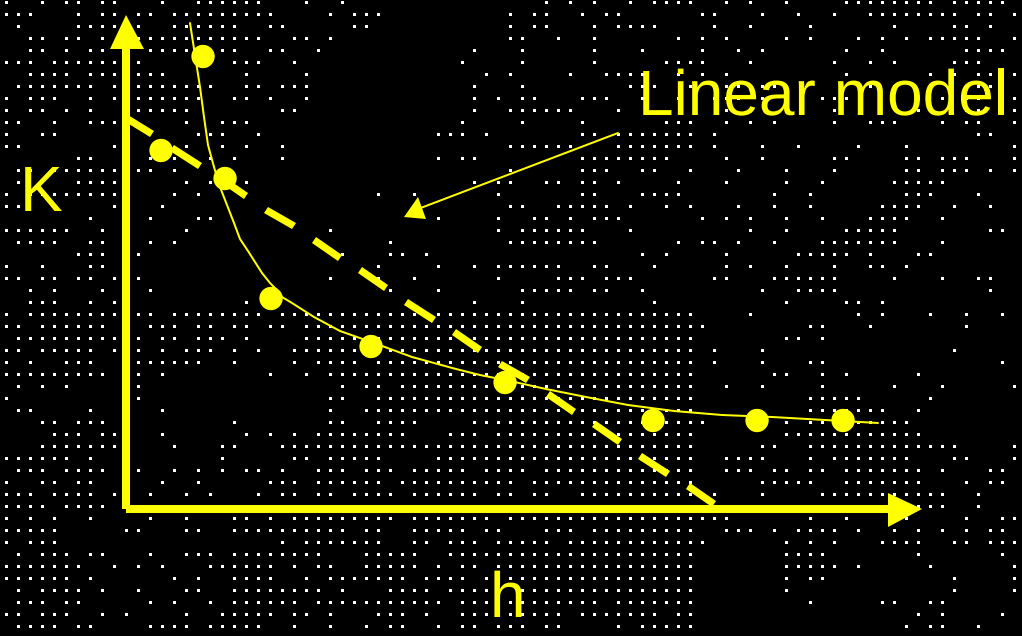
Minimum-output-error approaches
(e.g., maximum-likelihood)

✡ No!

- Non-unique solution.
- Insurmountable computational burden: limited to 2-D, small number of zones, low resolution image.
- The large number of data sets from hydraulic tomography presents a great numerical challenge.

2. Classical Co-kriging:

- Unique estimate: conditional mean.
- Linear estimator: limited to mildly heterogeneous systems.
- It cannot take full advantage of head information.



✡ No!

- Numerical difficulties if the number of observation is large.

3. Our sequential inverse approach:

- a. Successive linear estimator (SLE)

- Iterative Geostatistical Approach for estimating conditional moments.

1. Yeh et al., WRR, 32(1), 85-92, 1996
2. Zhang and Yeh, WRR, 33(1),63-71, 1997
3. Hughson and Yeh, WRR, 36(2?), 2000

- b. Execute SLE sequentially

- Propagates conditional moments sequentially.

- Considers spatial structure of geological formation.
- Incorporates point measurements.
- uses the non-linear relationship between *h* and *K*. Thus, reveals more heterogeneity than classical co-kriging.
- Estimates conditional mean fields--unique--and address uncertainty.

Yes!

Required input for our inverse model:

1. Mean, variance, correlation scales of hydraulic conductivity.

   Core samples, well logs, geophysics.

2. Pressure head/discharge data sets.

3. Point measurements of conductivity if any.

EFFECTS OF UNCERTAINTY IN INPUT

- **Variance of Conductivity**

  - Relies on correlation and cross-correlation

  - No impact

- **Mean of Conductivity**

  - A shift of the conductivity values

  - The same heterogeneity pattern

- **Correlation Scales**

  - Average dimensions of heterogeneity

  - Diminishes when point measurements are used for conditioning

- **Gravel Packs**

  - Artificial structure introduced to aquifer system

  - Incompatible with natural correlation structure

  - Omission influences estimates

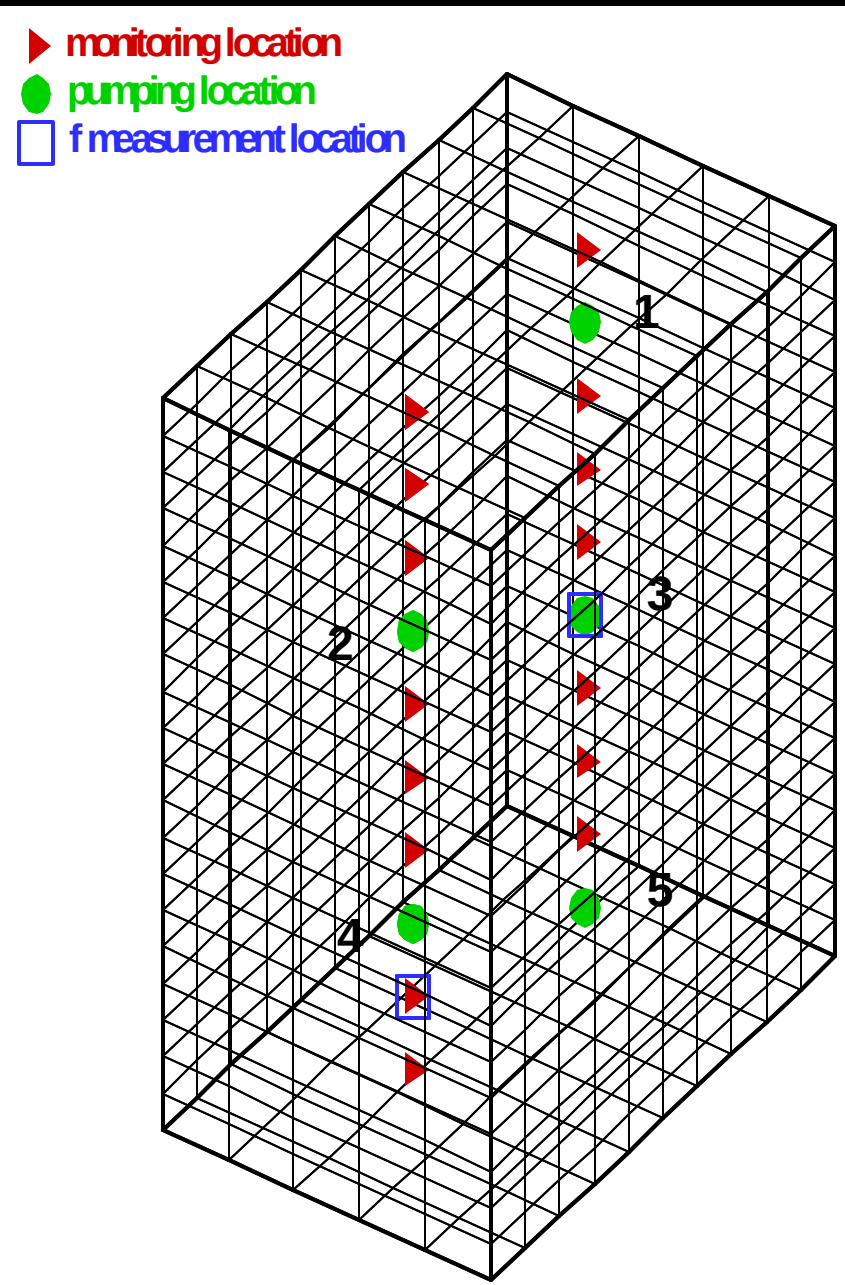
- **Errors in Head Measurements**

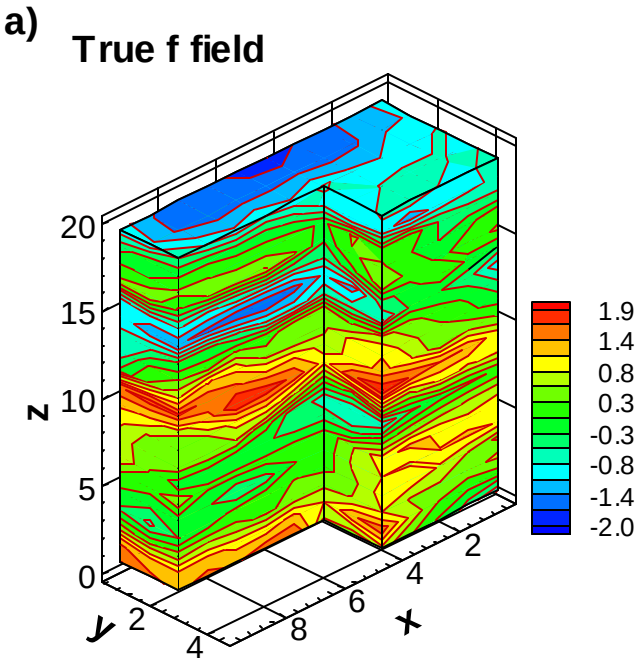
  - Significant!

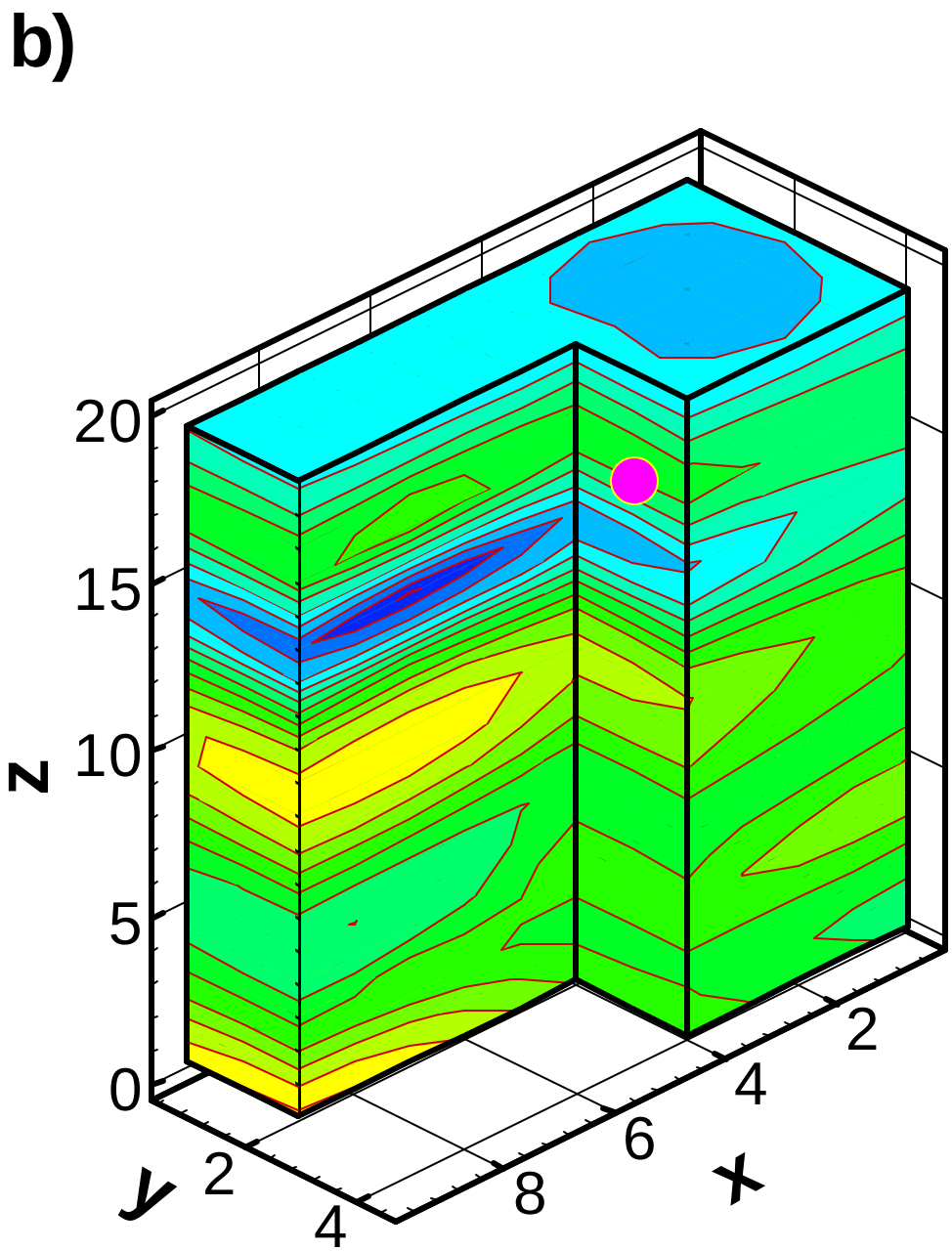
  - Increase pumping rate to increase the signal to noise ratio to reduce the impacts

3-D EXAMPLE

- Dimensions: 10 m x 5 m x 20 m
- Total elements: 1000
- Geometric mean of conductivity: 0.3452 m/hr
- Variance of lnK = 0.63
- Horizontal correlation scale (λ_x): 12 m
- Vertical correlation scale (λ_z): 4 m
- Use optimal network design
- Use 2 K measurements, one on each well




a)
True f field
20
15
10
5
0
z
2
4
y
8
6
4
2
x
1.9
1.4
0.8
0.3
-0.3
-0.8
-1.4
-2.0


b)
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z
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y
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6
4
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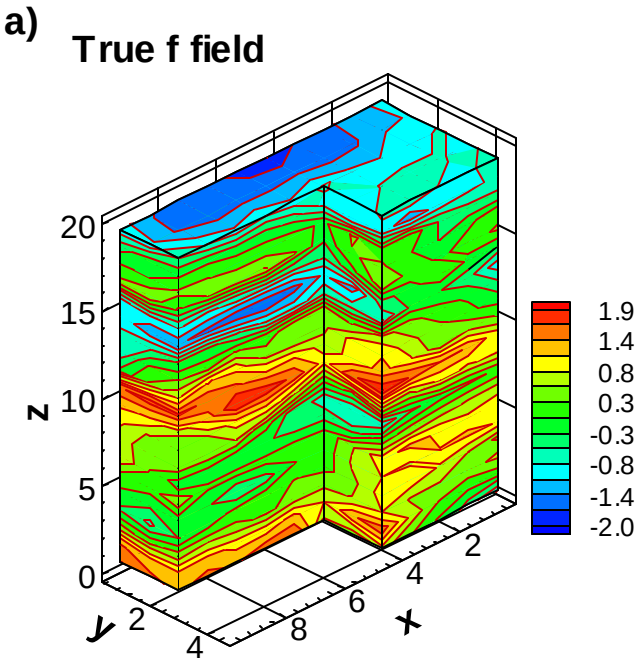
x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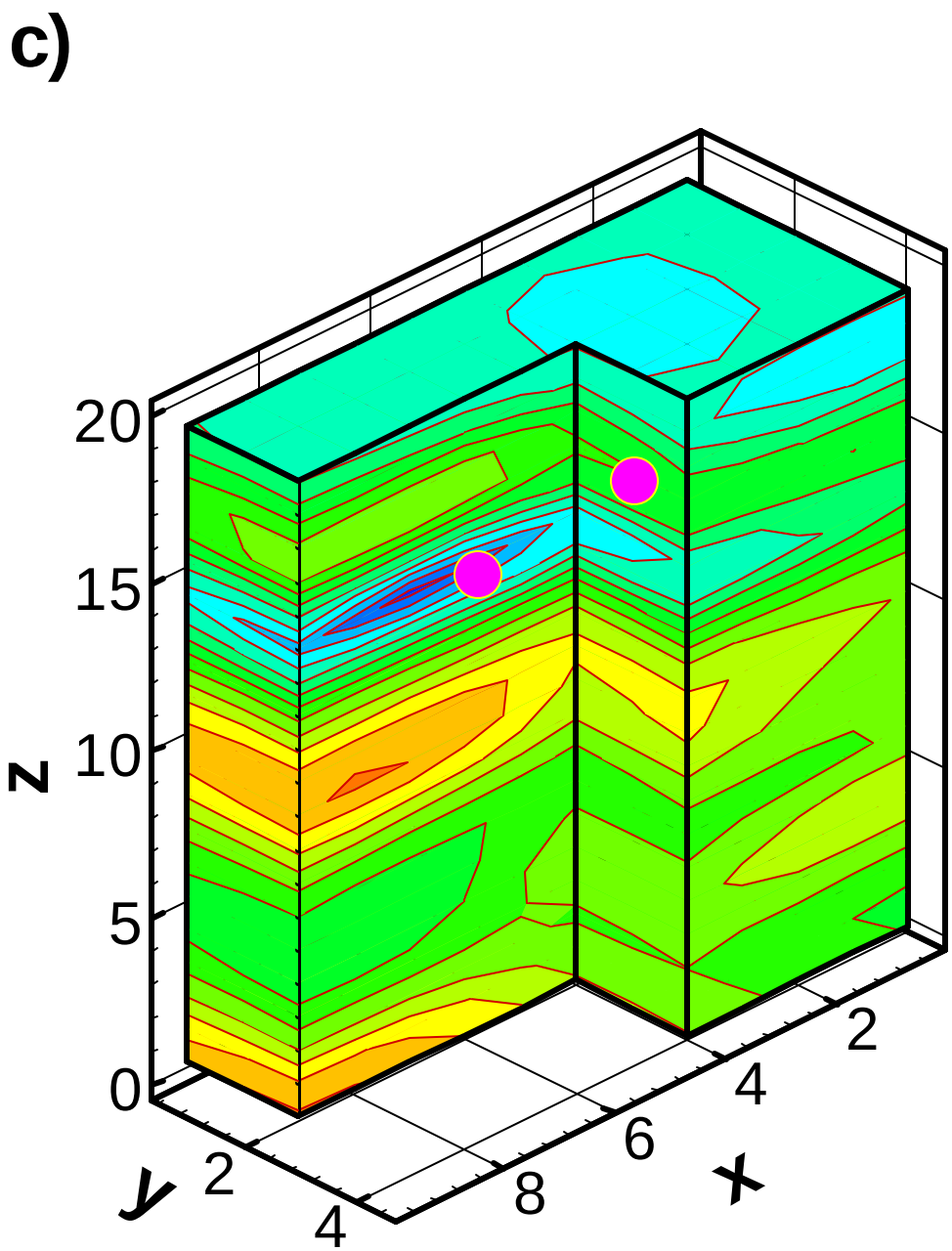
-2.0


c)
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15
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z
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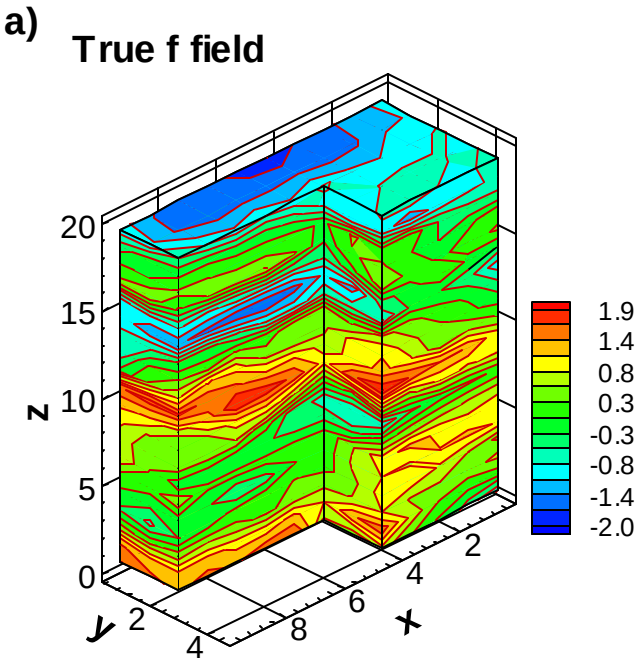
4
y
8
6
4
2
x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True f field
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z
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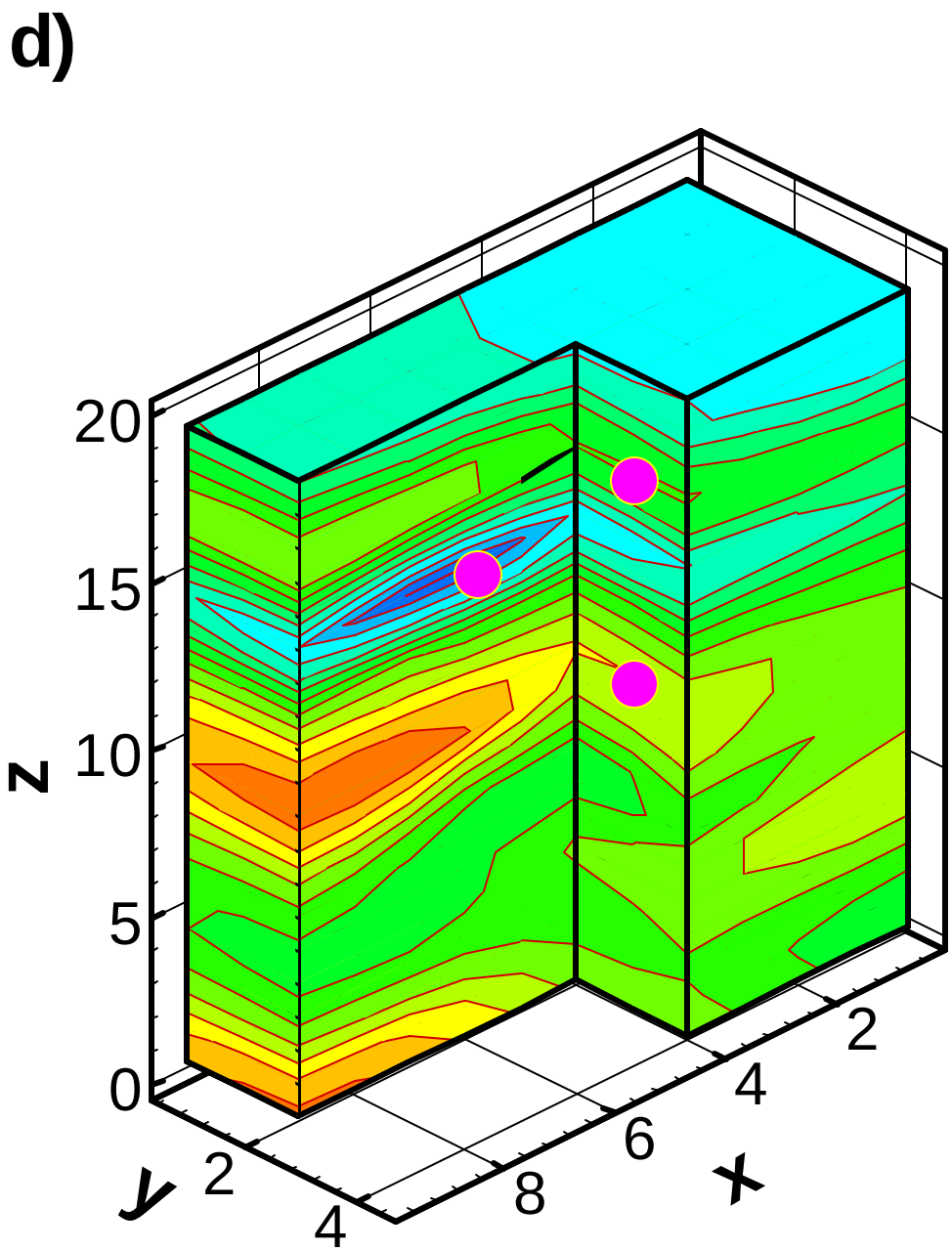
x
1.9
1.4
0.8
0.3
-0.3
-0.8
-1.4
-2.0


d)
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10
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z
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y
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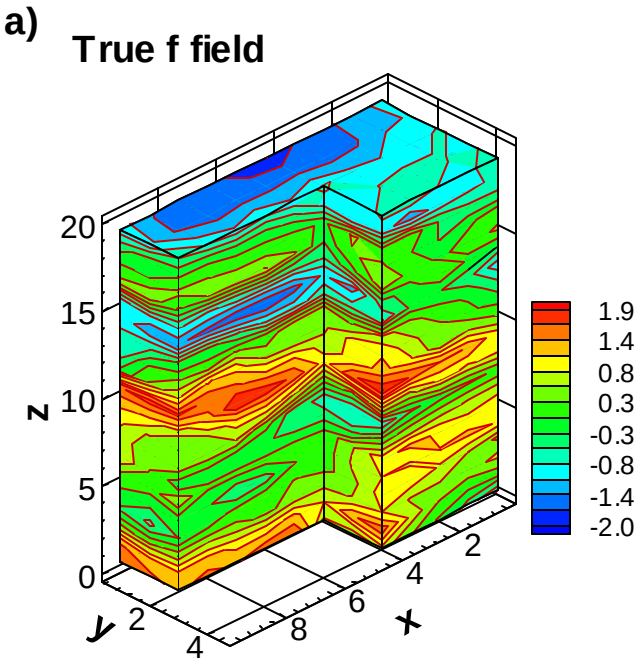
6
4
2
x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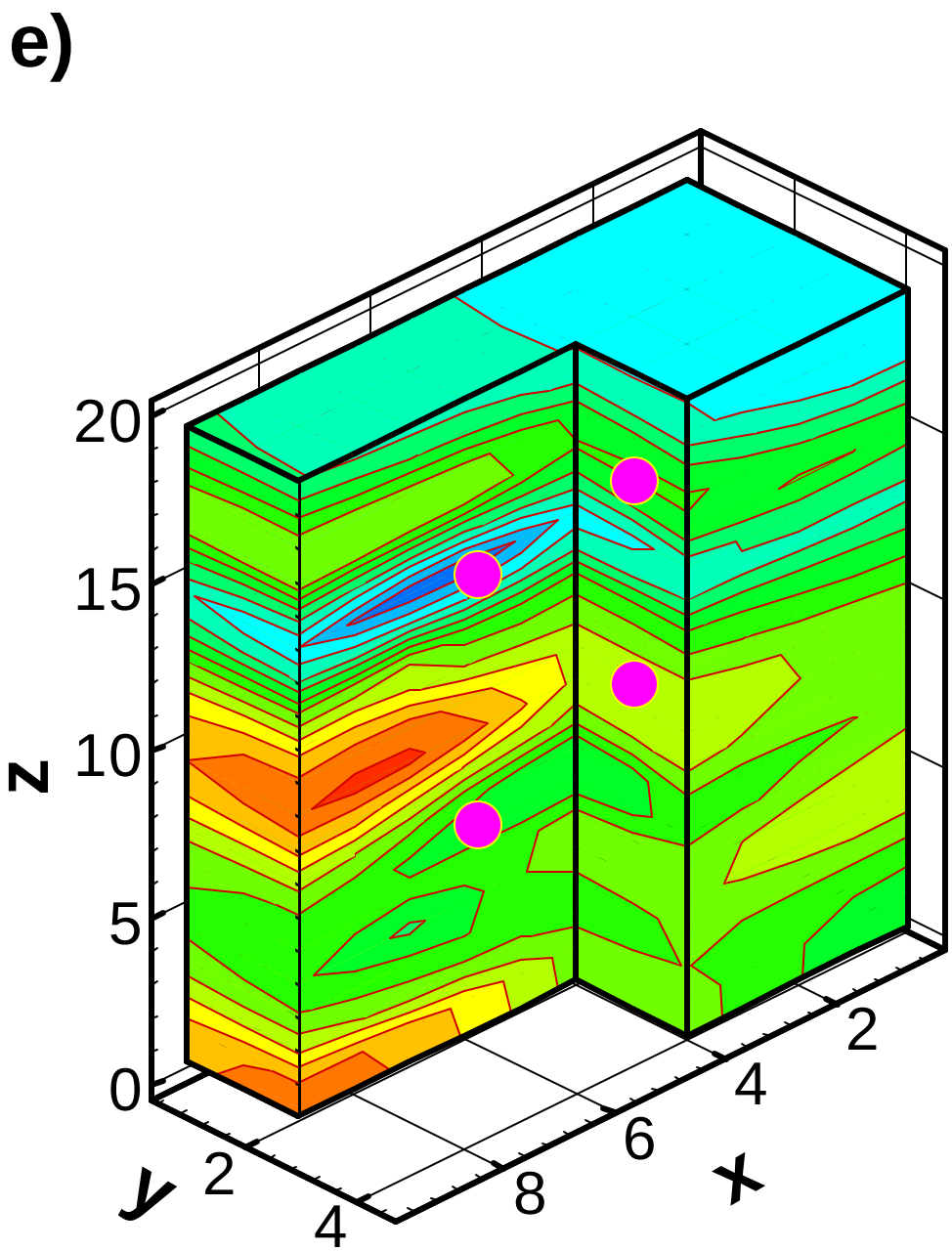
-0.3
-0.8
-1.4
-2.0


e)
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z
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y
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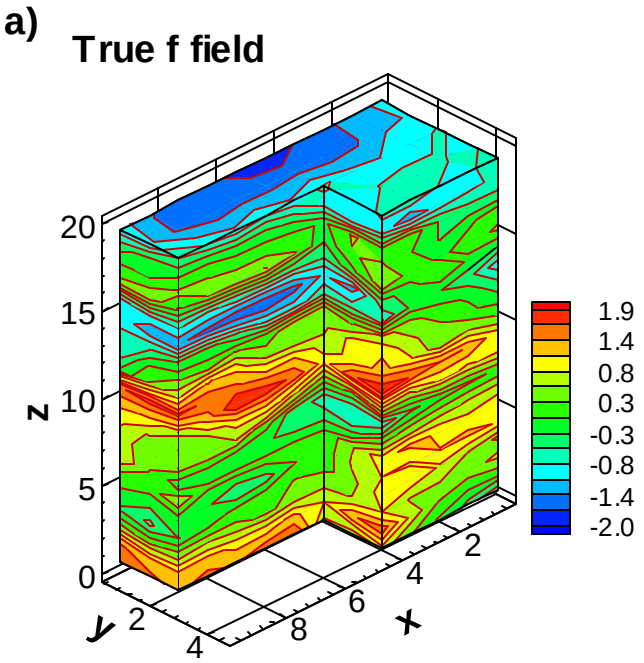
6
4
2
x


a)
True f field
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15
10
5
0
z
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4
y
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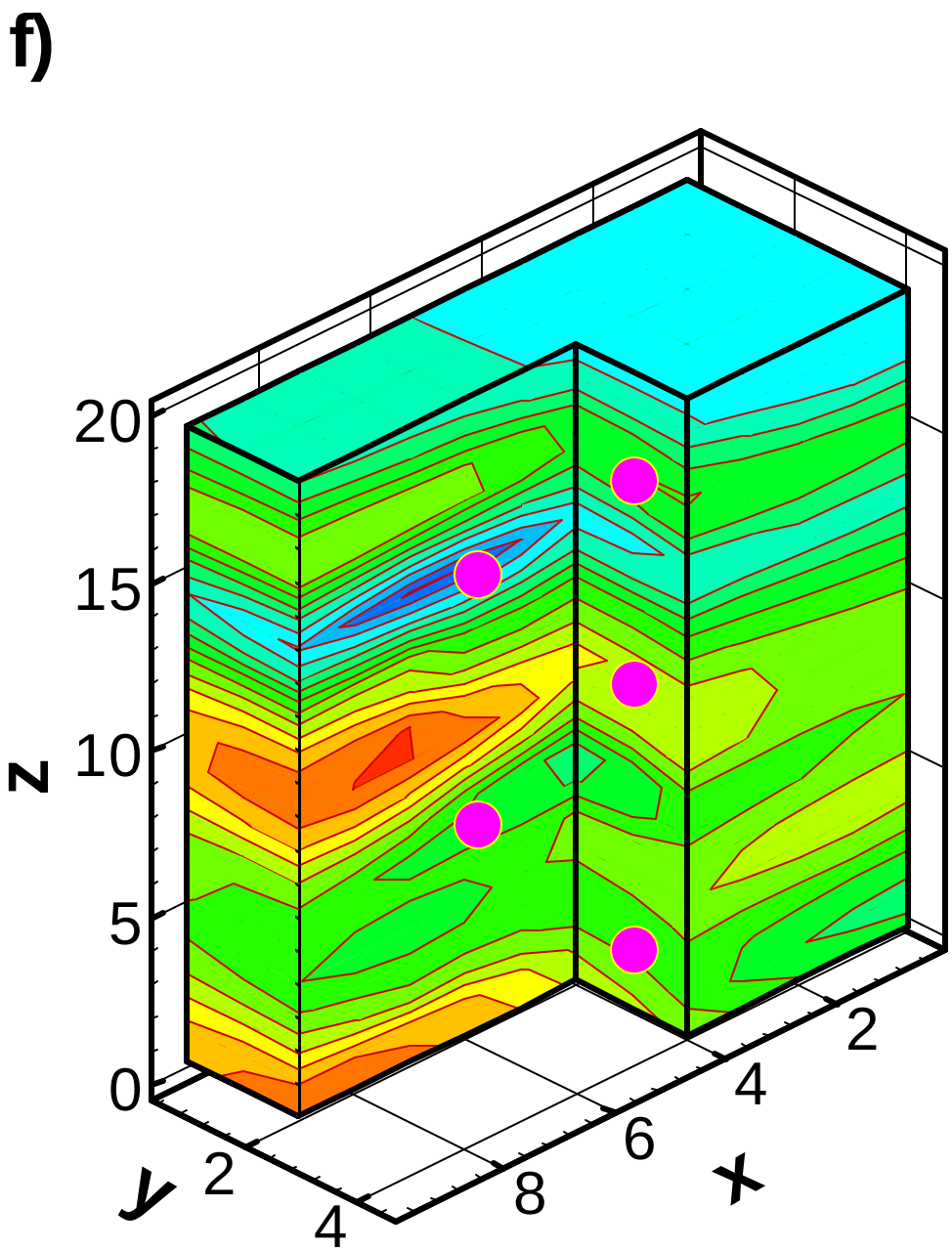
x
1.9
1.4
0.8
0.3
-0.3
-0.8
-1.4
-2.0


f)
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0
z
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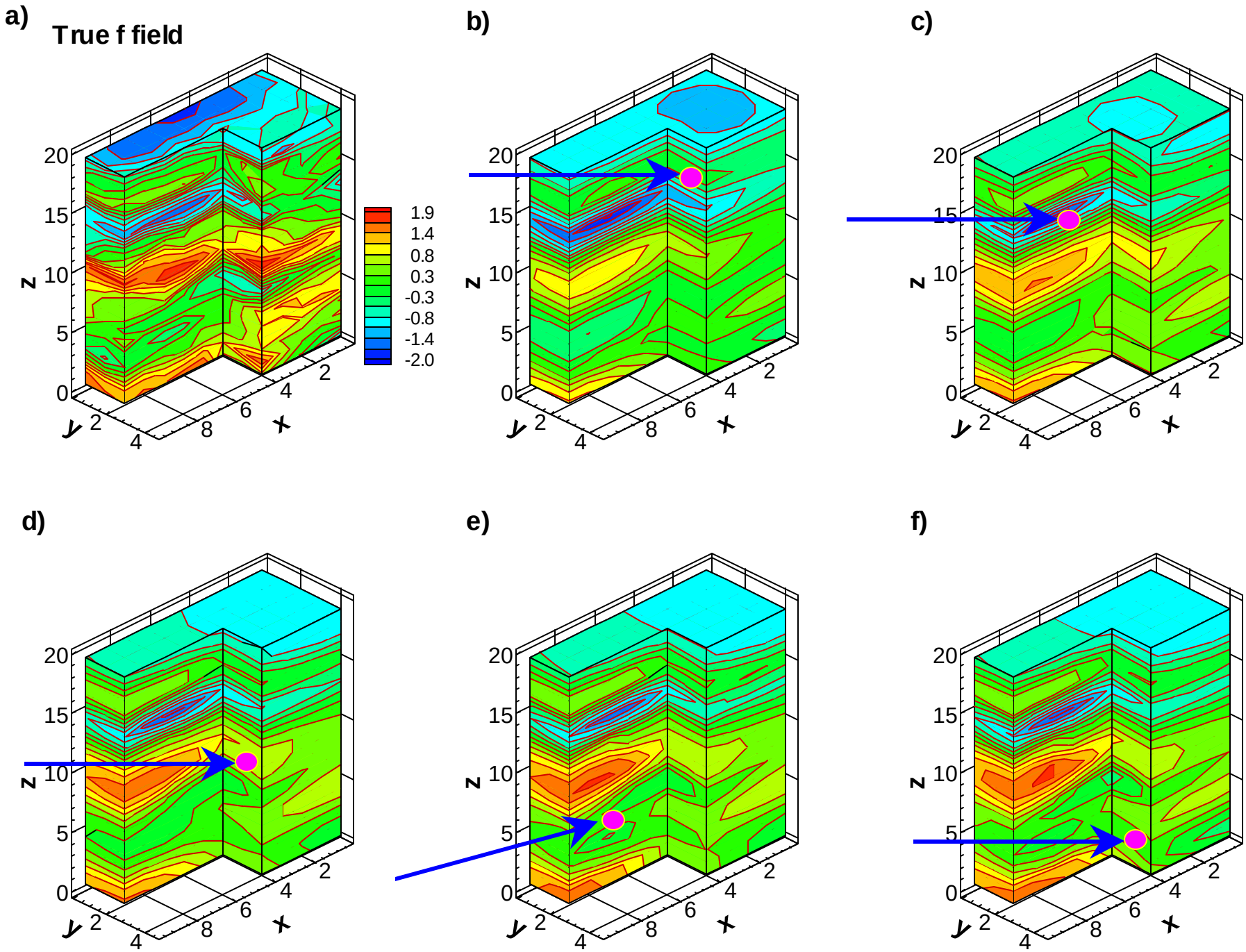
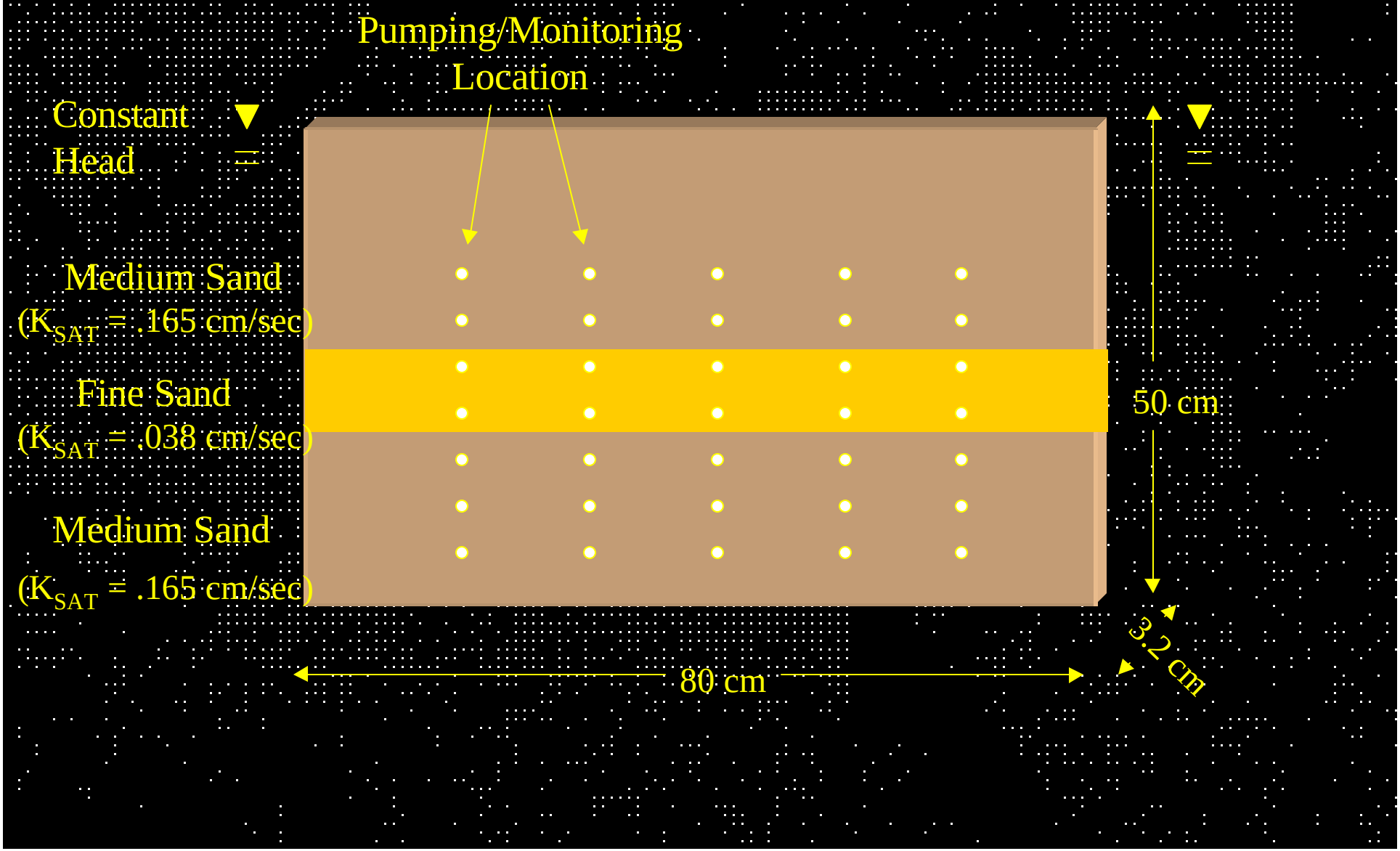
4
y
8
6
4
2
x

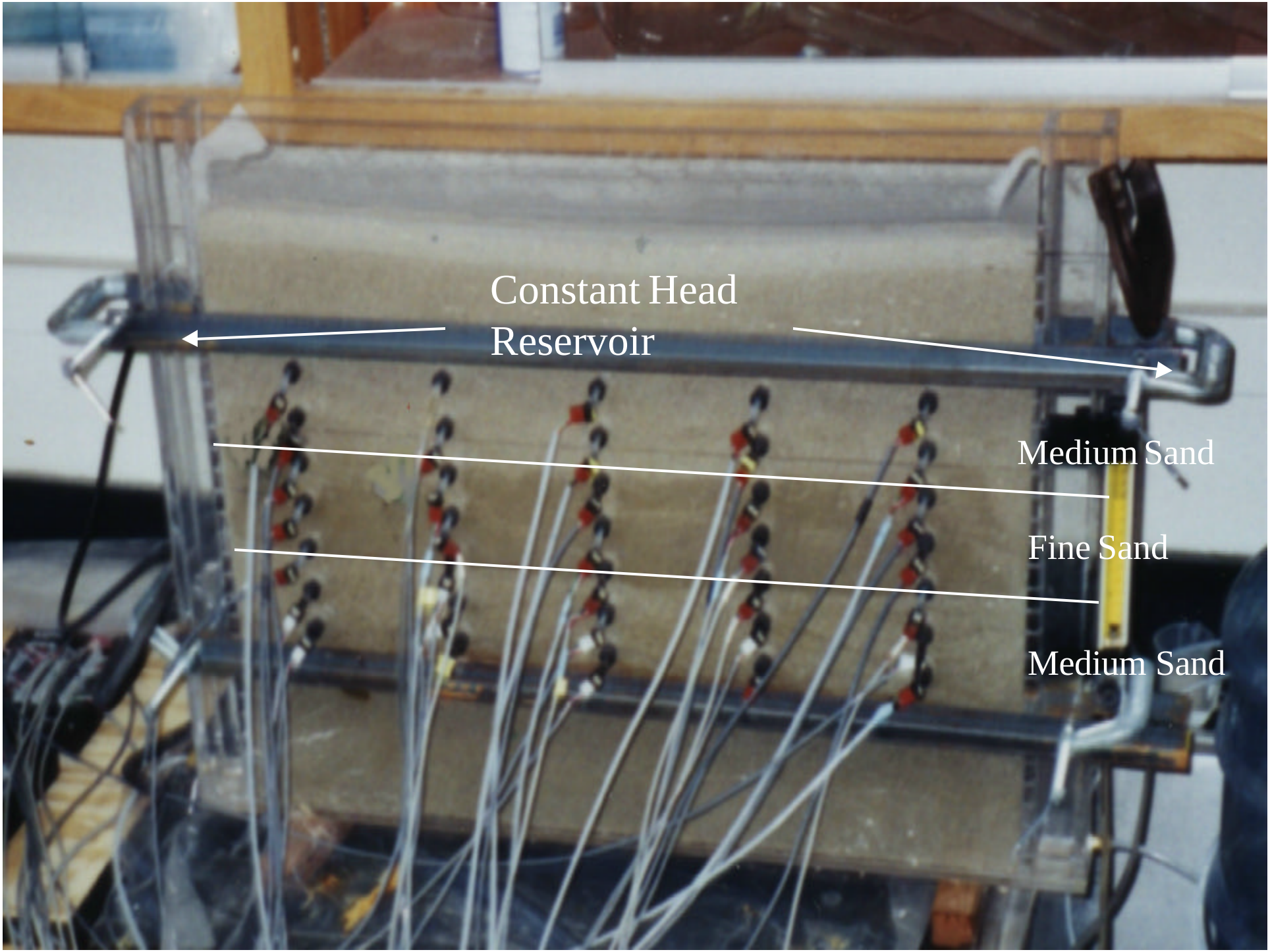

a)
True f field
b)
c)
d)
e)
f)
z
y
x
1.9
1.4
0.8
0.3
-0.3
-0.8
-1.4
-2.0

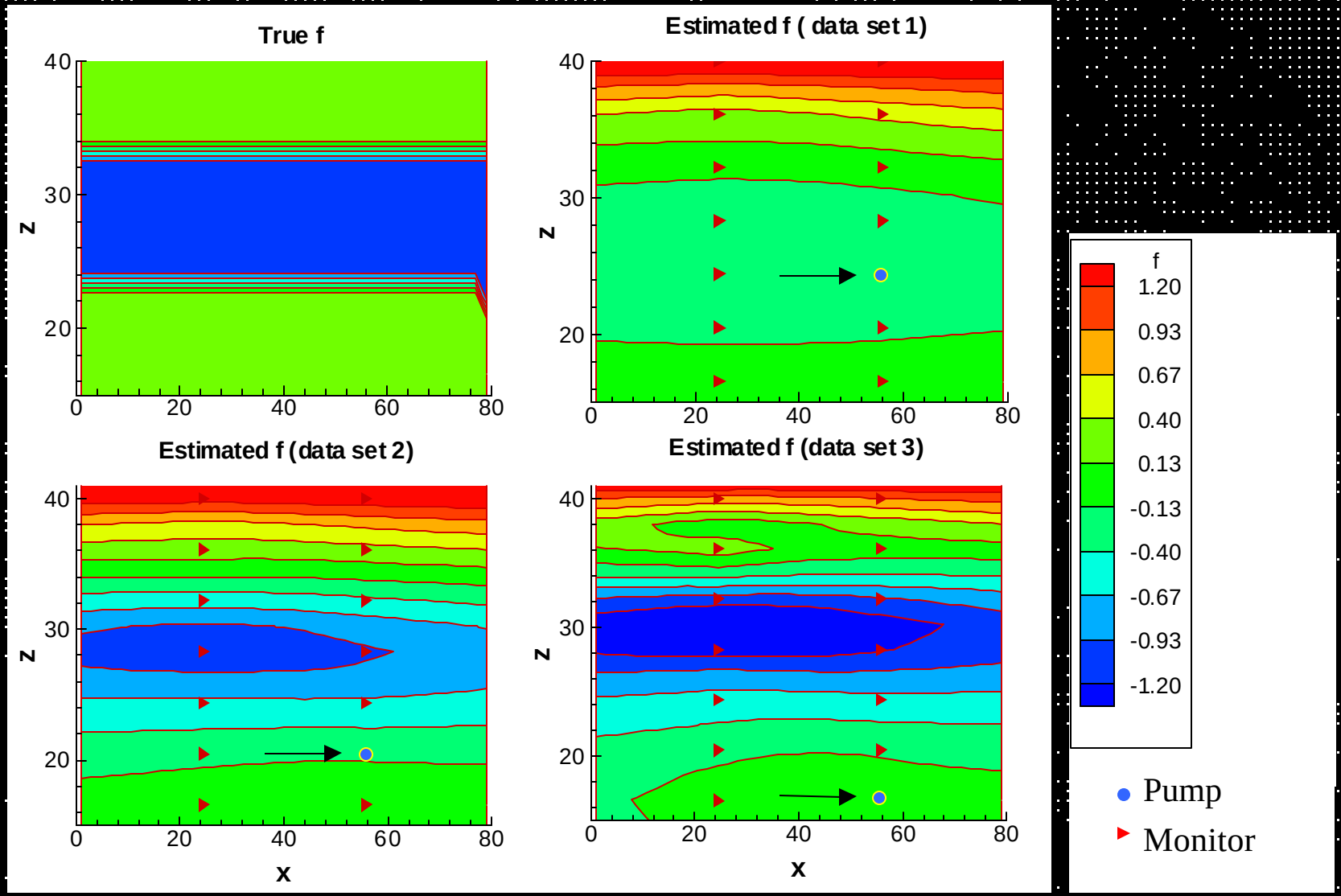
Too good to be true?

Sandbox experiments!

SANDBOX DESIGN




Constant Head
Reservoir
Medium Sand
Fine Sand
Medium Sand


True f
Estimated f (data set 1)
Estimated f (data set 2)
Estimated f (data set 3)
z
x
0
20
40
60
80
f
1.20
0.93
0.67
0.40
0.13
-0.13
-0.40
-0.67
-0.93
-1.20
Pump
Monitor

It works!

In spite of uncertainties in input data and difference in scale and whatever!

FAQs:

1. How far apart the two wells?
2. How far apart the pressure sensors?
3. Where to position the pump?
4. How many pumping tests?

↓

Network Design

ANSWERS

- **Optimal network design**

  - Spacing between the two wells = 0.5 λ_x
  - Pressure sensor vertical interval <= 0.5λ_z
  - Optimal number of pumping locations = aquifer depth / λ_z

CONCLUSIONS

Hydraulic Tomography & SLF (Patent in progress)

- Promising (needs field verification)
- Reveals greater detailed heterogeneity
- Cost-effective: well spacing = 0.5 x.
- High resolution imaging requires closely spaced pressure head measurements, depending on the vertical dimensions of heterogeneity.

Pneumatic Tomography

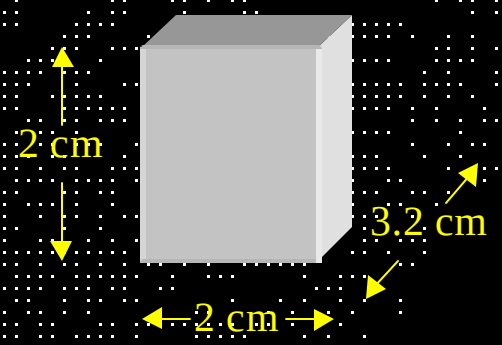
- Cost effective means to characterize preferential flow paths in the dry vadose zone.

- Great tool for detecting connectivity of fractures in unsaturated fracture rocks.

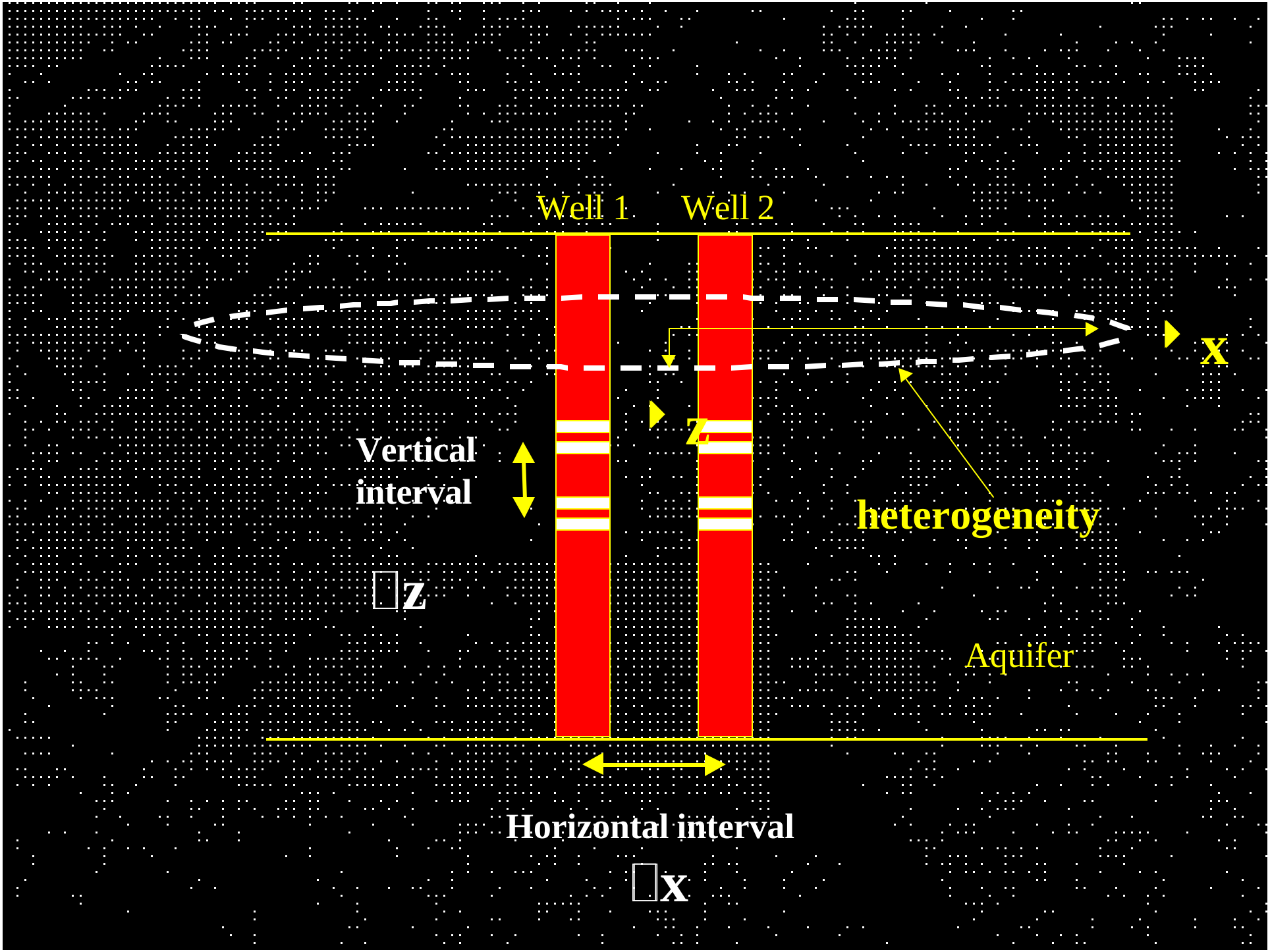
Thank you!

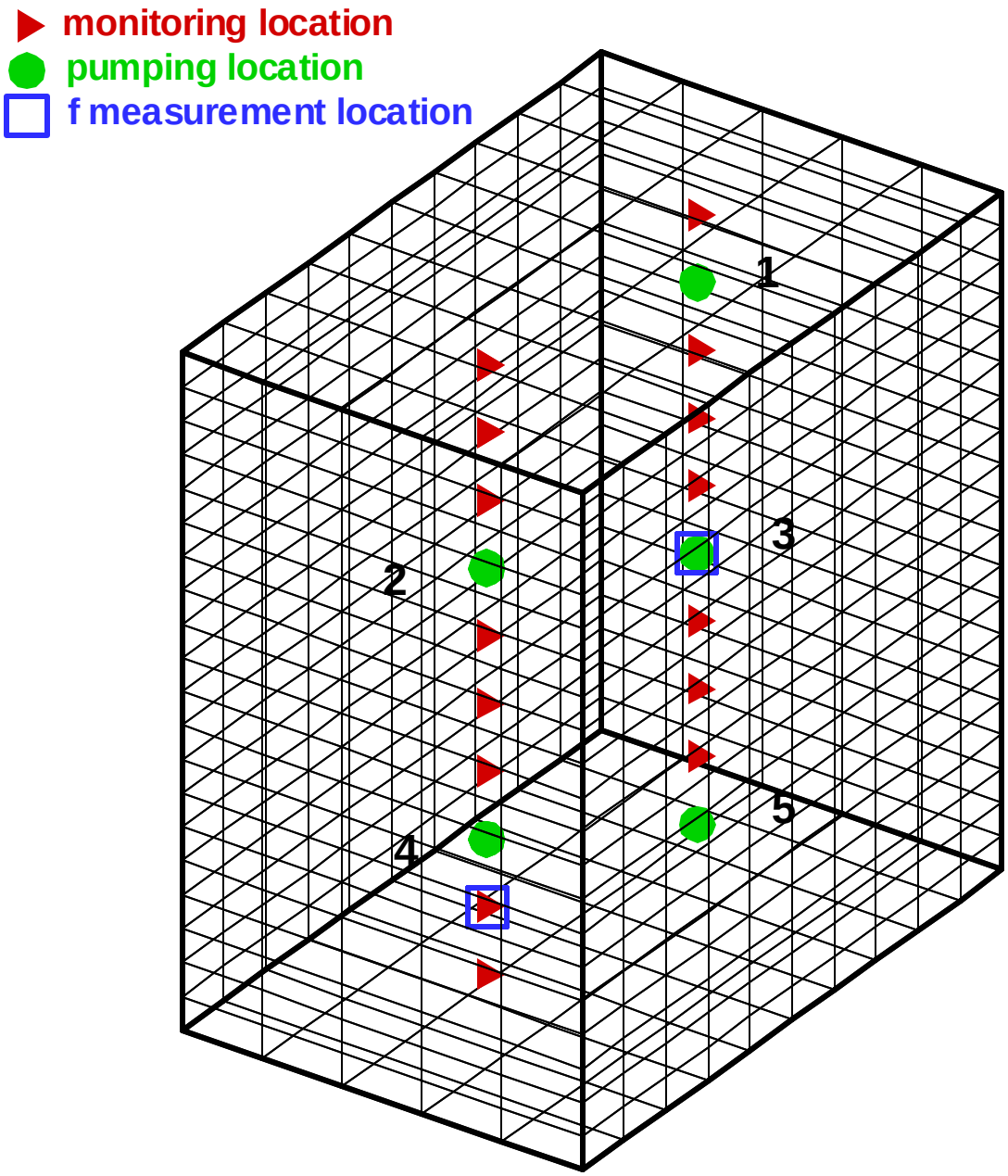
MODEL INPUTS

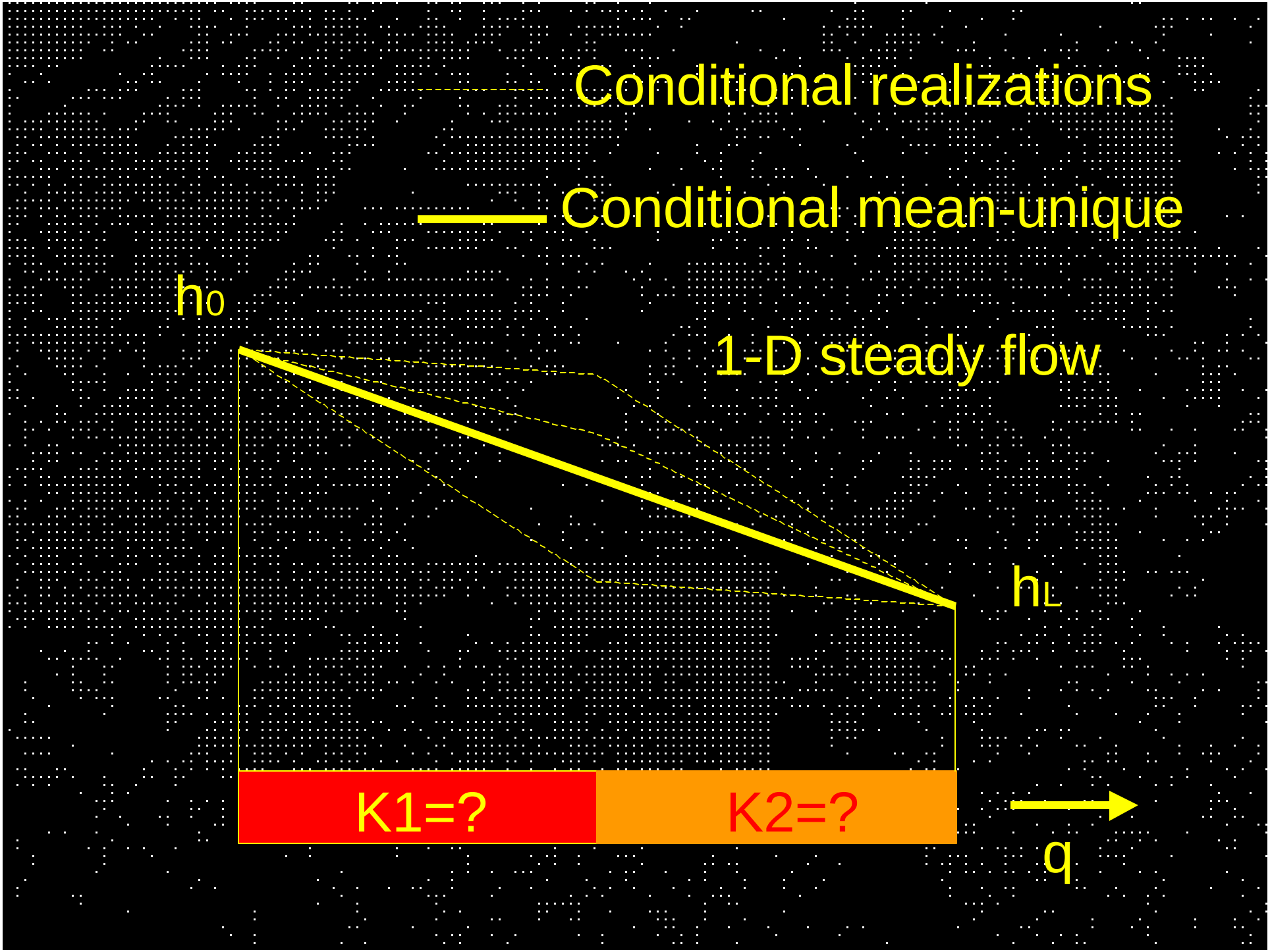
- 1,066 elements; Element dimensions



- Mean conductivity --- classical aquifer test
- Covariance functions --- exponential
- horizontal / vertical correlation scales -- 10m /.3m
- Head/discharge data

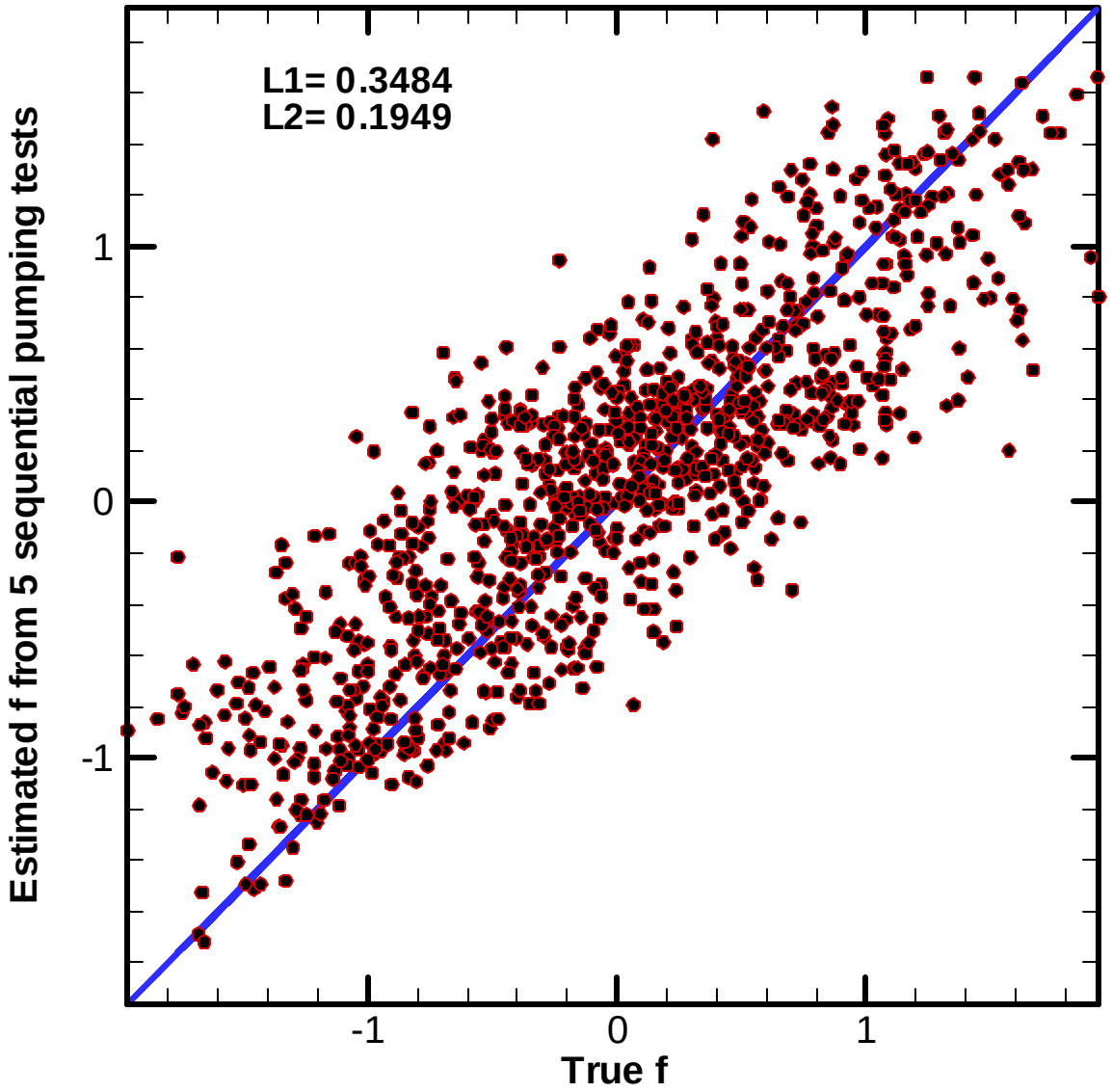

Well 1
Well 2
x
z
Vertical interval
heterogeneity
Δz
Aquifer
Horizontal interval
Δx


monitoring location
pumping location
f measurement location
1
2
3
4
5


Conditional realizations
Conditional mean-unique
h0
1-D steady flow
hL
K1=?
K2=?
q

- b. Benefits of Executing SLE sequentially

- Efficiently process the large number of data sets yielded by hydraulic tomography.
- Incorporate other types of information (i.e., solute arrival time) .


L1= 0.3484
L2= 0.1949
Estimated f from 5 sequential pumping tests
True f
1
0
-1
-1
0
1